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Dilute alloys of uranium have been shown to resist cavitational swelling, and a great deal of attention has been devoted to determining the limits of stability of the various compositions during irradiation.[1-3] Optimum alloys would be easier to develop if the basic metallurgical factors that promote swelling resistance were understood.

The basic driving force for cavitational swelling of uranium is the anisotropic growth (change of shape) of individual grains in the structure.[4] Alloying additions may increase resistance to swelling by inhibiting the anisotropic growth process. The anisotropic growth of the dilute uranium alloys is being established concurrently with the determination of their swelling behavior to test this hypothesis. To date, only heat-treated specimens have been irradiated, and the textures necessary to produce significant irradiation growth have generally not been present. In a few cases, however, enough texture has been generated during heat treatment to make a preliminary assessment of the effect of alloying additions on irradiation growth.

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* Summarized as a contribution from the audience at the Institute of Metal Discussion on "The Irradiation Effects in Uranium Alloys and Compounds," London, April 19-20, 1966.

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TEST PROCEDURES

Test specimens of various compositions (Table I) were one-inch long cylinders, contained in stainless steel capsules that were filled with NaK during irradiation. The specimens were machined from cast-and-extruded stock and heat treated by several procedures (Table I). The crystallographic texture of the specimens was measured by X-ray diffraction to yield a growth index[5] in the length direction.

The specimens were irradiated at central temperatures of 200° to 500°C for exposures up to 5000 MWD/T. Length changes after irradiation were used as a measure of the anisotropic growth of the specimens.

GENERAL DESCRIPTION OF RESULTS

Effect of Composition and Heat Treatment

The alloy specimens changed in length during irradiation by amounts that depended upon composition and heat treatment. As shown in Fig. 1 for specimens in the beta-heated, oil-quenched condition (Heat Treatment 1 in Table I), length changes for most compositions were within ±15% after exposures of 5000 MWD/T. However, the composition U-1000 ppm Si-810 ppm Al (Alloy F) increased >30%. No other correlation of growth with alloy concentration was evident among the alloys, except that all dingot (low carbon) specimens decreased in length. The alloy with the greatest length decrease was the dingot composition U-280 ppm Fe (Alloy $\bar{E}$).

The anisotropic growth of the alloy specimens was caused by crystal textures produced during heat treatment.[6] As would be expected, alternative heat treatments markedly altered the growth of the various alloys, as illustrated for selected alloys in Fig. 2. Though the effects of alternative heat treatments were not uniform from alloy to alloy, results may be summarized generally as:

1. Alpha-phase annealing at 520°C after a beta-heat oil-quench treatment (Heat Treatment 2) produced little change in anisotropic growth as compared to just the beta oil quench treatment; however, annealing at 600°C (Heat Treatment 2A) increased growth markedly.

2. Quenching from beta temperatures to 500°C in salt for 2 min or to 450°C in Pb-Sn alloy for 5 min for isothermal transformation prior to water quenching increased length more than oil quenching; this increase may have been due to the effect of the final water quench on specimens that were incompletely transformed during isothermal transformation. Air cooling from beta temperatures (Heat Treatment 6) also increased growth as compared to oil quenching, although the increase was less than that for the isothermal transformation, water quench treatments.

3. Gamma treatments at 800 and 950°C with oil quenching (Heat Treatments 9 and 11) and with furnace cooling from gamma to beta temperatures before oil quenching (Heat Treatment 5) produced about the same growth behavior as beta treatment with oil quenching. Alpha annealing at 400 and 500°C after a gamma heat and oil quench (Heat Treatments 10B and 10) had no additional effect, and at 600°C (Heat Treatment 10A) increased growth only slightly.

Dependence on Irradiation Conditions

Average growth rates (%length change/10,000 MWD/T) of the various alloys are given in Table I. The growth rates were relatively constant with increasing temperature except for alloys that swelled markedly (Fig. 3). In the latter cases (dashed lines in Fig. 3), the swelling significantly increased the length of samples irradiated at temperatures above swelling thresholds. For these alloys, the growth rates were calculated on the basis of the length changes observed for low-temperature specimens only.

CORRELATION OF ANISOTROPIC GROWTH WITH TEXTURE AND SWELLING

Growth rates depended on the magnitude of the texture formed during heat treatment. Plotting growth rate against the growth index for all alloy specimens revealed a wide scatter of data points. The growth indexes were measured on single specimens of the alloy stock; structural variations in texture could be high and precision of a growth index was estimated ±0.02. The scatter, attributable to imprecision of data, was thus considerable. In cases in which data for the same alloy from two different irradiation tests were available, growth rates could be correlated with growth indexes. These data are shown by solid lines in Fig. 4 for the Alloys F, Y, $\overline{W}$, and H. For only one alloy, W, the data points were not consistent. The dashed line in Fig. 4 is for Alloy $\overline{E}$, which had an uniquely large negative growth rate. The dotted line represents the behavior of unalloyed ingot uranium that was established by a large number of specimens in a previous test.[7] The growth of the unalloyed ingot uranium specimen (Alloy O) in the present test agrees well with these previous data.

Extrapolation of the correlation lines to unit growth index yielded effective b-axis growth coefficients[8] for the alloys. The growth coefficients for the five alloys illustrated in Fig. 4 are compared with that for unalloyed uranium in Table II.

The growth coefficients of the alloy specimens were less than those observed for unalloyed uranium, except for Alloy $\overline{E}$, which had a somewhat larger growth coefficient. The large length changes of

Alloys F and E resulted from relatively high growth coefficients, rather than from high degrees of texture induced during heat treatment.

These results indicate that a correlation exists between the growth coefficients and cavitational swelling susceptibility.[1A] Except for Alloy E, the dilute uranium alloys were less susceptible to cavitational swelling than unalloyed uranium, in accord with their smaller growth coefficients. Alloy E was at least as susceptible to swelling as unalloyed uranium. The growth coefficients for the other alloys are not sufficiently precise to be correlated with their swelling susceptibility.

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TABLE I

Anisotropic Growth Rates of Dilute Uranium Alloy Specimens During Irradiation

Alloy Designations	Base*	Composition, ppm Fe	Si	Al	Cr	Mo	Heat Treatment†	Avg Growth Rate**, % per 10,000 MWD/T
A	Ingot	350	(50)††	700	-	-	1	+8
							3	+14
							11	+9
							12	+11
B	Ingot	350	360	1000	-	-	1	+10
							2	+2
							2A	+25
							5	+16
							9	+10
							10	+16
							10A	+2
							10B	+23
$\bar{B}$	Dingot	350	310	870	-	-	1	-19
C	Ingot	240	250	(10)	-	-	1	+11
D	Ingot	(85)	350	915	-	-	1	-5
$\bar{E}$	Dingot	280	(30)	(20)	-	-	1	-44 (230 -280°C)
F	Ingot	(80)	1000	810	-	-	1	+65
							5	+37
							9	+27
							10	+31
							10A	+41
G	Ingot	(85)	350	(10)	-	-	1	-9
H	Ingot	(55)	720	(10)	-	-	1	+17
M	Ingot	250	240	255	-	-	1	+23
							2	+20
$\bar{M}$	Dingot	250	220	220	-	-	1	-14
O	Ingot	(105)	(25)	(5)	-	-	1	0 (230 -280°C)
$\bar{O}$	Dingot	(60)	(10)	(30)	-	-	1	-14 (230 -280°C)
U	Ingot	265	365	735	220	-	1	-9
							6	+27
							8	+47
							8A	+32
V	Ingot	135	95	(65)	-	-	1	-5
W	Ingot	(60)	330	(10)	-	1000	1	+24
$\bar{W}$	Dingot	(60)	400	(35)	-	1000	1	-24
X	Dingot	120	120	110	-	-	1	-23
Y	Ingot	345	360	860	-	980	6	+17
							8	+58
							8A	+37
							10A	0

Footnotes on following page

Footnotes for Table I

* Base Metal - Ingot(500 ppm C); Dingot(30 ppm C)

† Heat Treatments

1 Beta treat 725°C 10 min, oil quench

2 Beta treat 725°C 10 min, oil quench; alpha anneal 520°C 1 h, oil quench

2A Beta treat 725°C 10 min, oil quench; alpha anneal 600°C 5 h, oil quench

3 Gamma treat 800°C 20 min, water quench

5 Gamma treat 800°C 20 min, furnace cool to 725°C, hold 10 min, oil quench

6 Beta treat 725°C 10 min, air cool

8 Beta treat 725°C 10 min, quench to 500°C 2 min, water quench

8A Beta treat 725°C 10 min, quench to 450°C in Pb-Sn - hold 5 min, water quench

9 Gamma treat 800°C 20 min, oil quench

10 Gamma treat 800°C 20 min, oil quench; alpha anneal 520°C 1 h, oil quench

10A Gamma treat 800°C 20 min, oil quench; alpha anneal 600°C 5 h, oil quench

10B Gamma treat 800°C 20 min, oil quench; alpha anneal 400°C 7 h, oil quench

11 Gamma treat 950°C 20 min, oil quench

12 Gamma treat 950°C 20 min, oil quench; beta treat 725°C 10 min, oil quench

** Growth Rate determined by length changes at 5000 MWD/T, averaged over temperature range 225-425°C, except values in parentheses ( ) which were determined from length changes at 2500 MWD/T at the temperatures given. Growth rate = $(\frac{\Delta L}{L} \times 100) \frac{1}{10{,}000 \text{ MWD/T}}$

†† Parentheses denote concentrations of naturally occurring impurities.

TABLE II

Growth Coefficients of Uranium Alloys

Alloy Designations	B-Axis Growth Coefficient,* % per 10,000 MWD/T
E	~2500
O (Unalloyed uranium)	2100
F	900
Y	400
W	350
H	170

* Growth Coefficient = $\left(\frac{\Delta L}{L} \times 100\right) \frac{1}{10{,}000\ \mathrm{MWD/T}}$

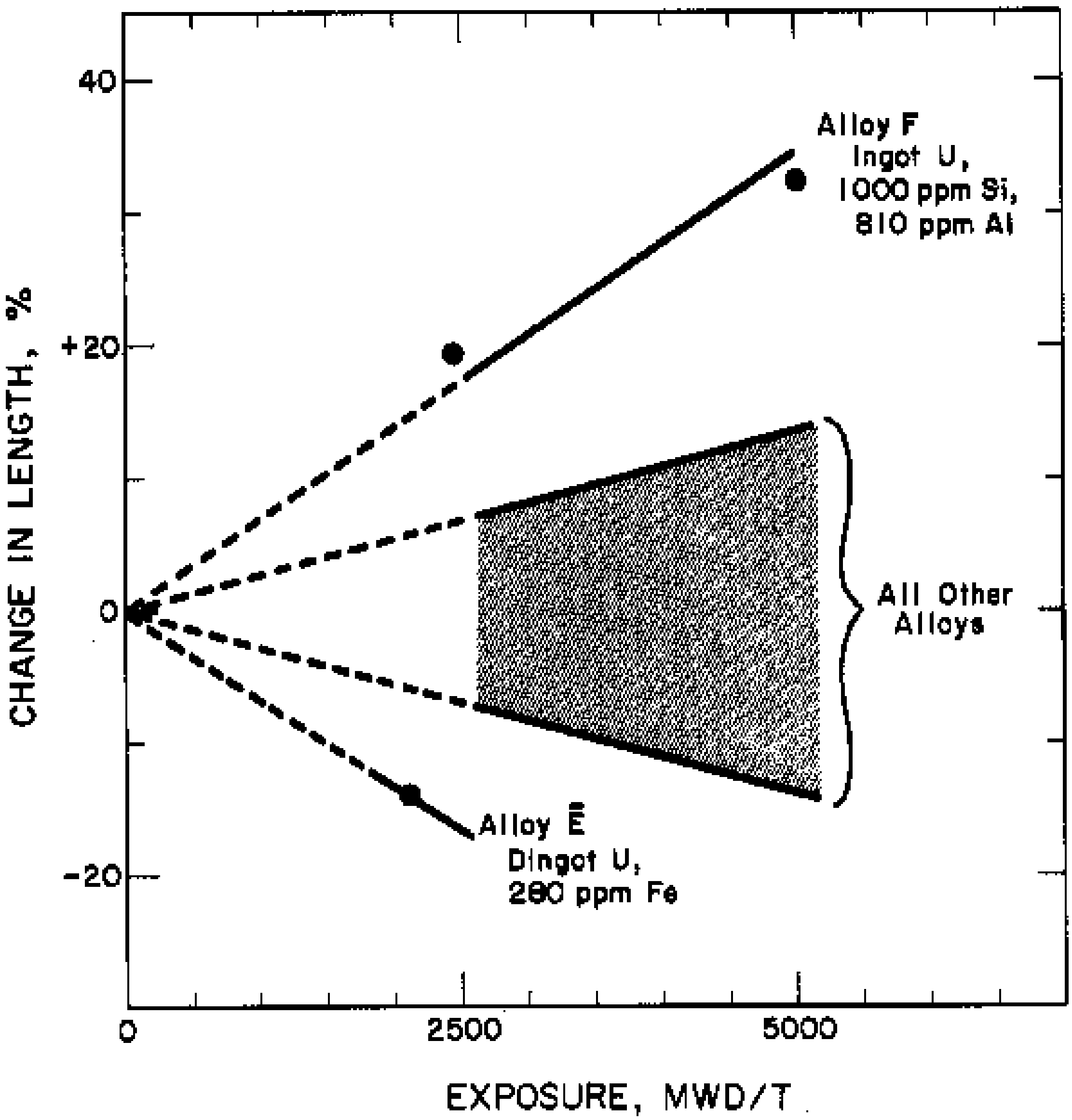

FIG. 1 LENGTH CHANGES PRODUCED BY IRRADIATION OF BETA-TREATED-OIL-QUENCHED SPECIMENS OF DILUTE URANIUM ALLOYS

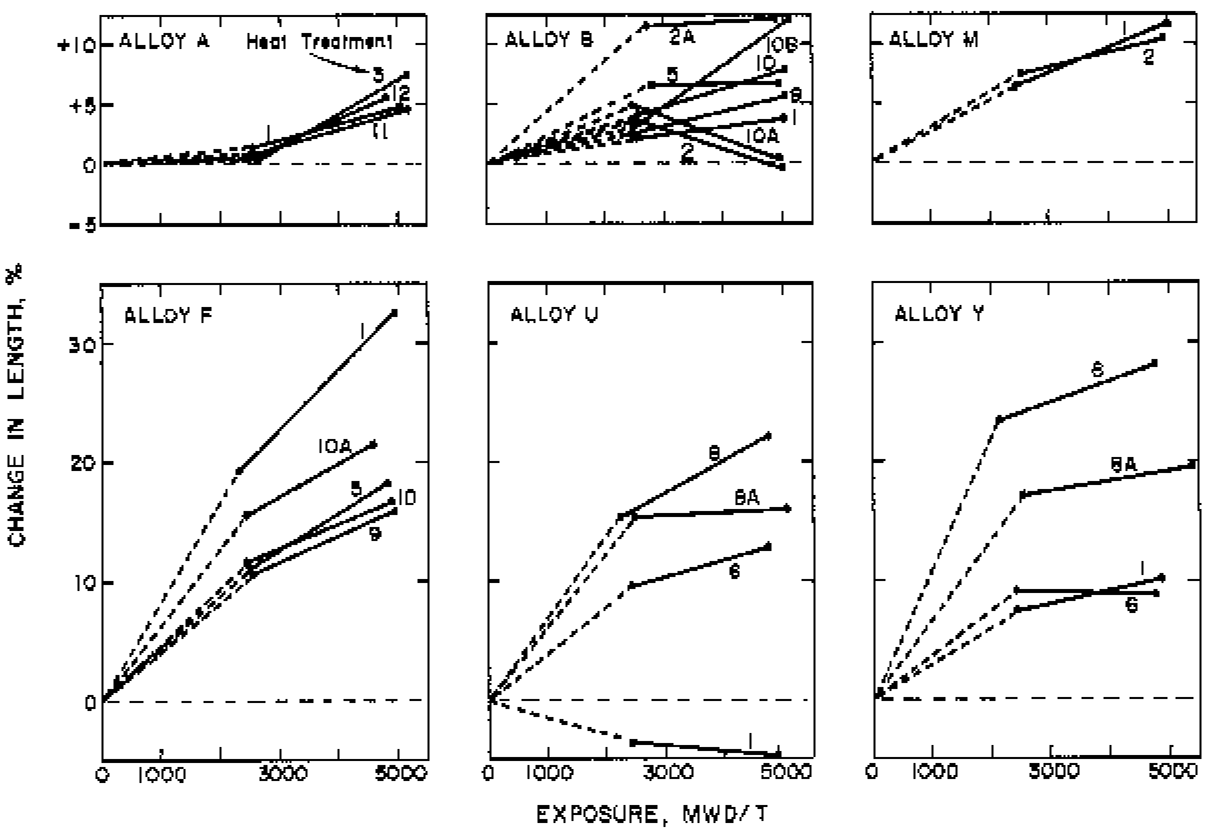

FIG. 2 EFFECT OF HEAT TREATMENT ON LENGTH CHANGE OF DILUTE URANIUM ALLOY SPECIMENS DURING IRRADIATION

(Compositions and heat treatments are given in Table I.)

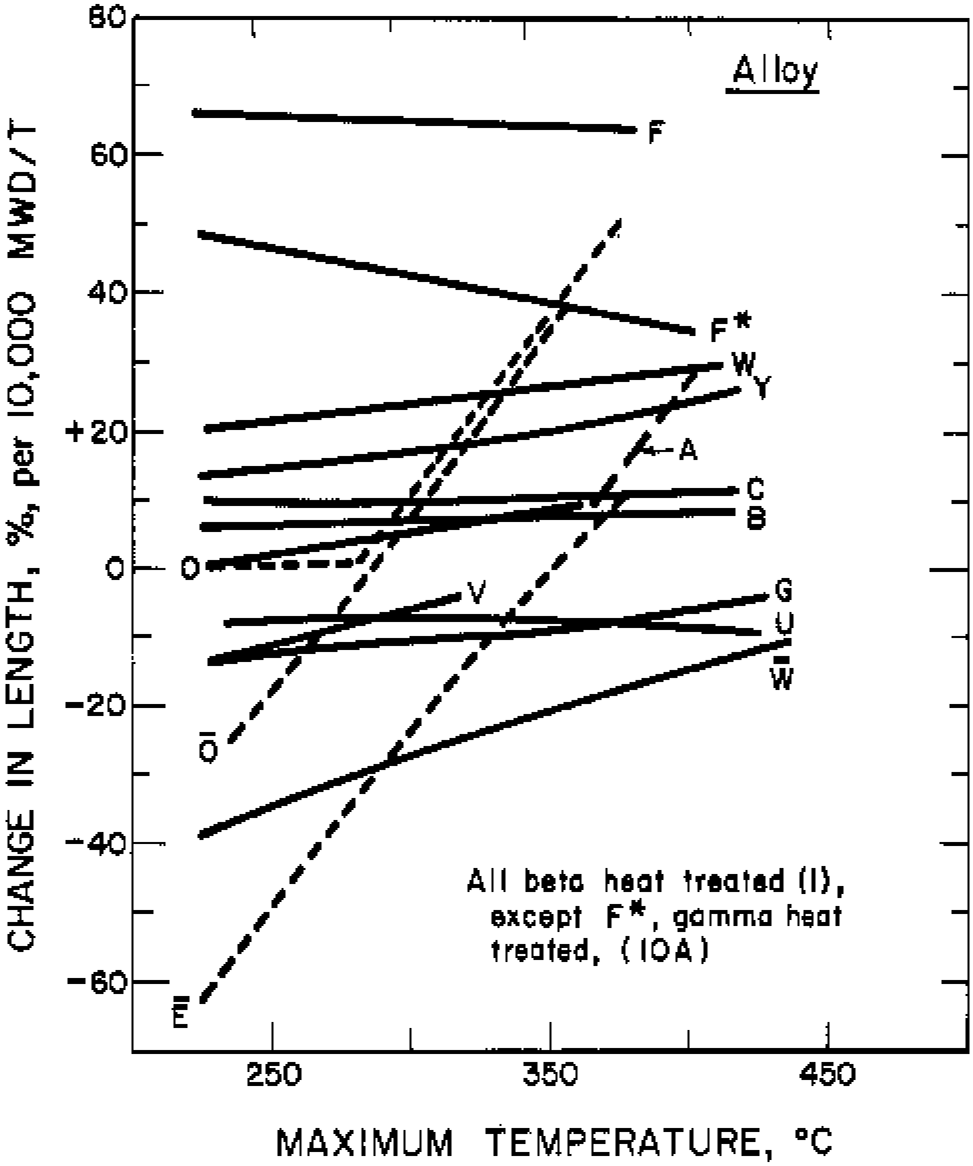

FIG. 3 DEPENDENCE OF GROWTH RATES ON CENTRAL TEMPERATURES OF REPRESENTATIVE DILUTE URANIUM ALLOY SPECIMENS

(Alloy compositions and heat treatments are given in Table I. Dotted lines indicate compositions that swelled significantly at higher temperatures, producing length changes due to volume increases as well as anisotropic growth.)

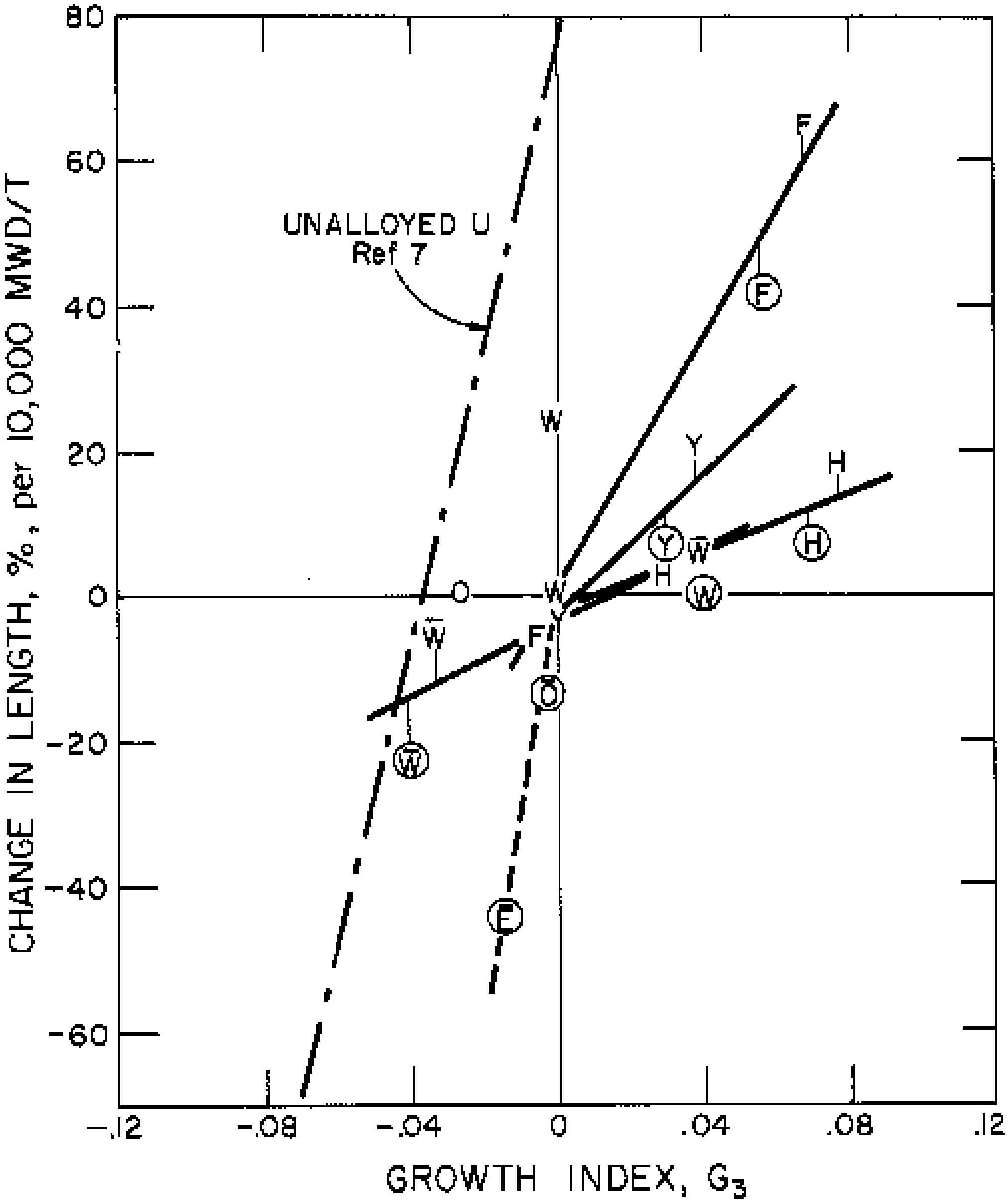

FIG. 4 DEPENDENCE OF AVERAGE GROWTH RATE ON TEXTURE MEASURED BY X-RAY GROWTH INDEX TECHNIQUE

Alloy codes are given in Table I. Circled letters designate data obtained in this test (Table I); uncircled letters designate data obtained in a previous test.